# WASHABILITY OF AIR TOXICS IN MARKETED ILLINOIS COALS

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## INTRODUCTION AND BACKGROUND

The 1990 Clean Air Act Amendments (CAA) require that the health risks resulting from the atmospheric emissions of 189 hazardous air pollutants (HAPs) from various industrial sources be assessed and, if needed, emission limits be established [U.S. Public Law 101-549, 1990]. Of these 189 HAPs, 16 elements (As, Be, Cd, Cl, Co, Cr, F, Hg, Mn, Ni, P, Pb, Sb, Se, Th, U) occur in coal in trace or minor quantities, and may be emitted into the atmosphere during combustion. Electrical utilities are presently exempt from compliance with the CAA requirements for HAPs. This may, however, change after the U.S. Environmental Protection Agency (EPA) completes its risk analyses and promulgates emission standards as prescribed by law.

The U.S. Geological Survey (USGS) has a substantial amount of data on HAPs in channel samples of coals from various regions of the U.S. The U.S. EPA will use this database for its risk assessment of HAPs emissions from coal-fired power plants. Because Illinois coals shipped to utilities are cleaned at conventional preparation plants, and conventional cleaning decreases levels of most HAPs in marketed Illinois coals relative to channel samples [Demir et al., 1994a], the USGS data on channel samples would overestimate the emission of HAPs from combustion of these coals at utilities.

Recent reviews of the environmental aspects of trace and minor elements in coal (Swaine, 1989; Clarke and Sloss, 1992; Wesnor, 1993) indicated that (1) modern pollution control systems can trap up to more than 90% of fly ash generated during coal combustion and (2) trace elements that "escape" during combustion are either emitted in gas phase or attached to ultrafine fly ash particles that are not captured by the pollution control systems. Highly volatile HAP elements (Hg, Cl, F) are mostly or partially volatilized in the flue gas, while less volatile ones (As, Cd, Pb, P, Sb) generally vaporize, oxidize, and then, upon cooling, condense onto the fly ash particles (Fig. 1). The least volatile HAPs (Mn, Th) are enriched in bottom ash and slag. Other HAPs (Se, Be, Co, Cr, Ni, U) exhibit mixed behavior depending on their mode of occurrence in the feed coal, the characteristics of coal and mineral matter, and types and operational conditions of combustion units.

Coal cleaning is an attractive alternative to costly post-combustion control of air toxics emissions from power plants. Reviews that summarized progress in the removal of trace and minor elements, including HAPs, via coal cleaning include Mezey [1977], National Research Council [1979, 1980], Wheelock and Markuszewski [1981, 1984], Streeter [1986], Kaiser Engineers [1989], Jacobsen et al. [1992], and Norton et al. [1986, 1989, 1992]. These reviews show that physical coal cleaning can be economical and effective for significantly decreasing the content of most HAPs prior to combustion. In general, physical cleaning becomes efficient if a high degree of comminution is utilized to free mineral matter from the macerals. Those elements associated (either physically disseminated or bonded chemically) with the macerals are not easily removed; in some cases, their concentrations may actually be enhanced in the cleaned coal. Recent studies [Paul and Honaker, 1994; Honaker and Reed 1994] indicated that mineral matter content of finely ground Illinois Basin coals can be effectively decreased using advanced gravity separators.

It has been generally recognized that the cleaning efficiency of gravity separators for fine-sized coal cannot be estimated from conventional, static float-sink (F-S) tests. Centrifugal F-S procedures, however, could successfully predict the cleanability of -28-mesh (<0.589-mm) size coal [Harrison, 1986; Franzidis and Harris, 1986; Cavallaro and Killmeyer, 1988; Ho and Warchol, 1988; Bosold and Glessner, 1988; Dumm and Hogg, 1988; Suardini, 1993].

The purpose of this study was to generate F-S washability data to estimate how much more the HAP content of marketed Illinois coals can be decreased if advanced gravity-based coal cleaning was used at coal preparation plants. Washability data for twelve HAP elements (As, Be, Co, Cr, Mn, Ni, P, Pb, Sb, Se, Th, U) in 27 coal samples ground to -100 mesh (<149 $\mu$m) and in 8 coal samples ground to -200 mesh (<74 $\mu$m) are reported and discussed.

## EXPERIMENTAL

### Samples and Sample Preparation

Each of the 27 samples of marketed coals was collected from a different coal preparation plant in Illinois. The samples are from five different regions of Illinois coal field (Fig. 2), and are preserved under nitrogen at the Illinois State Geological Survey (ISGS). Collection, preparation, and storage of the samples were described by Demir et al. [1994a,b].

Representative splits of the 27 samples were dry-ground in a hammer mill so that 90% of the particles were smaller than 100 mesh (149 $\mu$m). Also, eight of the 27 samples were wet-ground in a rod mill (700 grams coal + 700 mL tap water) generally for 30 minutes so that 90% of the particles were smaller than 200 mesh (74 $\mu$m). The coal slurry from the rod mill was filtered and air-dried. The -100 and -200 mesh samples were saved under nitrogen for the subsequent washability tests.

**Washability Tests**
A centrifugal float-sink (F-S) method based on the methods reported in Ho and
Warchol [1988] and Cavallaro and Killmeyer [1988] was used to determine the
washabilities of both ash and HAPs. The washability test procedure was as
follows:

(1)   Mix about 100-g of coal sample dried at 40°C overnight with 2 L of
      coalgrav® liquid (mixture of tetrachloroethylene and naphtha) with a
      specific gravity (s.g.) of 1.3 to generate a slurry containing about
      5% coal. Add dispersing reagent (Aerosol OT) to the mixture to achieve
      a dosage of about 5 mg reagent per g of coal.
(2)   Agitate the mixture with a mechanical stirrer for 6 to 10 minutes and
      then in an ultrasonic bath until no agglomeration persists (usually 2
      to 10 minutes).
(3)   Pour the slurry into 250-mL Teflon centrifuge bottles, tightly cap the
      bottles, and place the bottles in a centrifuge.
(4)   Centrifuge the slurry at 2000 rpm (about 880 g force for the centrifuge
      used) for 20 minutes.
(5)   Gently stir the float portion of the slurry in the bottles without
      disturbing the sink portion. Centrifuge the slurry again at 2000 rpm
      for 20 minutes.
(6)   Repeat step 5.
(7)   Gently pour the float out of the bottles onto a filter paper placed in
      a filter funnel. The pouring of the float portion usually does not
      significantly disturb the sink portion which becomes tightly compacted
      during the 1-hour centrifugation.
(8)   Filter the float and then wash it thoroughly, first with 250 mL of
      ethanol, and then 1.5 L of deionized water, to remove residues of
      coalgrav® and dispersing agent. Dry the float overnight at 40°C and
      weigh it.
(9)   Mix the sink from step 8 with 2 L of 1.4 s.g. coalgrav®, and repeat
      steps 2 through 8. A small amount of lower s.g. liquid trapped in the
      wet sink during the preceding step does not measurably alter the s.g.
      of the new suspension.
(10)  Mix the sink from step 9 with 2 L of 1.6 s.g. coalgrav®, and repeat
      steps 2 through 8.
(11)  Wash, dry, and weigh the sink as in step 8.
(12)  Submit the <1.3, 1.3-1.4, 1.4-1.6, and >1.6 s.g. F-S fractions for
      chemical analysis.

**Chemical Analysis and Preparation of Cleaned Composite Samples**
The 27 samples of marketed coals were analyzed for the 12 HAPs and ash and
all of their F-S fractions were analyzed for ash using well-established
procedures for common coal analyses at the ISGS (Table 1). The combustible
materials content of each F-S fraction was calculated by subtracting its ash
and moisture contents from 100. Then a plot of %cumulative combustibles
recovery vs cumulative weight of F-S fractions was constructed for each F-S
test. Using these plots, the first two or three lightest fractions from each
test were successively combined so that the composite sample contained 80%
of the combustible materials in the parent coal. All 80%-combustibles
recovery products were analyzed for the 12 HAPs and ash.

**RESULTS AND DISCUSSION**
The analytical data for the feed coals and their clean washability products
(Table 2) were used to estimate the ability to remove HAP elements from
finely-ground marketed Illinois coals through the use of advanced gravity
separators. The ranges of average concentrations for 12 HAP elements in the
27 samples of marketed Illinois coals (Fig. 3) were as follows:

        <2  mg/kg:   Be, Sb, Se, Th
        2-10 mg/kg:  As, Co, U
        10-20 mg/kg: Cr, Ni, Pb
        >20 mg/kg:   Mn, P

The concentrations of all HAPs, except Be, in the coals were decreased (with
a few exceptions) as a result of F-S separation at -100 mesh size (Table 3,
Fig. 4). Some of the decreases (or enrichments) of element concentrations
calculated for some individual samples may be erroneous if the difference
between the concentration of a given element in the parent coal and that in
its clean F-S product is not greater than the analytical precision for that
particular element. Such decrease and enrichment errors, however, generally
cancel each other when mean values for the entire sample set are computed.
On average, Be was enriched in the -100 mesh washability products by 94% when
compared with the parent coals. This suggests that Be was finely disseminated
(perhaps organically associated) within the coal macerals. Because some of
Be tends to stay with bottom ash and slag during coal combustion (Fig. 1),
and because the mean concentration of Be in the marketed coals was only 1.3
mg/kg (Fig. 3), additional environmental risk due to an average of 94%
enrichment of this element could be very small.

The decrease in ash content ranged from 37% to 75% with an average of 53%
(Table 3, Fig 4). As a result, 9 of the 27 clean F-S products had ash
contents of 2.77% to 3.86% (Table 2). The average decreases for As, Mn, and
P exceeded that for ash, indicating that these three elements were somewhat
enriched in relatively coarse mineral grains that were effectively removed
during the F-S process; As was likely associated mainly with pyrite, Mn with
calcite, and P with apatite. Precombustion removal of As from coal is
important because of its relatively high atmospheric mobility during coal
combustion (Fig. 1). The decrease of Se, another element with relatively

high atmospheric mobility (Fig. 1), was smaller than that of As but still significant (37%). The average decreases for Cr(20%), Sb(19%), and U(11%) were relatively small. Although Sb can be mobilized by attachment to air-borne fly ash particles, its small concentrations (Table 2, Fig. 3) could limit any environmental risk associated with Sb emission from combustion of marketed Illinois coals. Atmospheric emissions of Cr and U are expected to be small because they tend to be fixed in coarse ash and slag during coal combustion.

Grinding the 8 coals to -200 mesh (<74 $\mu$m) resulted in greater average decreases for Sb, Se, and Th and a smaller decrease for Mn when compared with decreases obtained for -100 mesh (<149 $\mu$m) samples of the same coals (Table 4, Fig. 5). The changes in the amount of decrease of other elements and ash for -200 mesh samples relative to -100 mesh samples were not significant. It should be noted that additional tests with varying centrifuge speed and amount and type of dispersant should be conducted to determine whether the F-S separation efficiency for -200 mesh samples can be increased.

The marketed coal products are currently ground to 70% passing 200 mesh (74 $\mu$m) size for utilization in pulverized coal boilers which comprise over 90% of the combustion units used in Illinois [Honaker et al., 1994]. Therefore, because there would be no extra cost for grinding, an advanced coal cleaning strategy that would substantially decrease HAPs, as well as ash and sulfur, in Illinois coals beyond conventional cleaning can be economical. Furthermore, as much as 10% of the production of many coal preparation plants in Illinois is fine coal waste. An efficient and low cost cleaning of this fine coal waste would generate additional clean coal and thus increase revenues from mined coal. Using clean coal would not only reduce atmospheric HAPs emissions but also slagging and fouling at coal-fired power plants.

## SUMMARY AND CONCLUSIONS

Float-sink washability data on 27 samples of marketed Illinois coals indicated that, at -100 mesh (<149 $\mu$m) particle size and with an 80%-combustibles recovery, the ash contents of the coals can potentially be decreased by 37% to 75% with an average of 53%, beyond conventional cleaning, using advanced gravity-based coal cleaning. As a result, some of the clean products could have ash contents of less than 3%. Decreases in ash contents were accompanied by decreases in the levels of eleven HAPs (As, Co, Cr, Mn, Ni, P, Pb, Sb, Se, Th, U) investigated, with a few exceptions. The average decreases for As, Mn, and P exceeded that for ash. The average decrease of Se was smaller than that of ash but still significant (37%). Precombustion removal of As and Se from coal is important because of their relatively high atmospheric mobility during coal combustion. On average, Be was enriched in the washability products by 94% compared with the parent coals. Because of its low concentrations in the coals and its low atmospheric mobility, the enrichment of Be caused by fine coal cleaning could increase any related environmental risk only slightly. The average decreases for Cr(20%), Sb(19%), and U(11%) were relatively small. Although Sb can be enriched in air-borne fly ash particles, any environmental risk associated with atmospheric Sb emission could be small because marketed Illinois coals generally have Sb concentration of about 1 mg/kg or less. Most of Cr and U are expected to be fixed in coarse ash and slag rather than emitted into the atmosphere during coal combustion. The grinding of 8 of the coals to -200 mesh (<74 $\mu$m) increased the removal of Sb, Se, and Th, decreased that of Mn and did not significantly change those of other HAPs compared with the -100 mesh (<149 $\mu$m) samples of the same coals. An efficient and low-cost fine coal cleaning of marketed Illinois coals could reduce not only the atmospheric HAPs emissions but also slagging and fouling at coal-fired power plants.

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**Table 1.** Relative precision and detection limits of methods commonly used for analyses of HAPs and ash in coal samples

| Element | Relative precision % | Average detection limit | WDXRF | AAS | INAA | OEP | PyroIC |
|---|---|---|---|---|---|---|---|
| Major and minor oxides (%) | | | | | | | |
| MnO | ash 5 | 0.01 | X | | | | |
| P$_2$O$_5$ | ash 5 | 0.02 | X | | | | |
| Trace elements (mg/kg) | | | | | | | |
| As | coal 7 | 1.0 | | | X | | |
| Be | ash 5 | 0.5 | | | | X | |
| Cd | ash 10 | 2.5 | | X | | | |
| Co | coal 5 | 0.3 | | | X | | |
| Cr | ash 2 | 7.0 | | | X | | |
| F | coal 10 | 20.0 | | | | | X |
| Hg | coal 15 | 0.01 | X** | | | | |
| Ni | ash 10 | 15.0 | | X | X | | |
| Pb | ash 20 | 25.0 | | X | | X | |
| Sb | coal 10 | 0.2 | | | X | | |
| Se | coal 10 | 2.0 | | | X | | |
| Th | coal 5 | 0.4 | | | X | | |
| U | coal 15 | 3.0 | | | X | | |

| Constituent | Absolute precision (%) | Accuracy (%) | ASTM method (1992) |
|---|---|---|---|
| Ash | 0.10 | 0.5 | D5142-90 |

\* WDXRF = wavelength-dispersive x-ray fluorescence spectrometry
  AAS = atomic absorption spectrometry
  INAA = instrumental neutron activation analysis
  OEP = optical emission (photographic) spectrometry
  PyroIC = pyrohydrolysis and ion chromatography
\*\* Hg by cold vapor atomic absorption spectrometry

**Table 2.** Chemical composition of samples of marketed Illinois coals (feed) and their clean F-S fractions at 80% combustibles recovery (product). Ash values are in wt% and elemental values are in mg/kg (all values are on a dry basis). One-half the detection limit was used, for those values less than the detection limit, in the computations of means and standard deviations.*

| FEED COAL NO. | REGION | MESH SIZE | Ash coal | Ash prod. | As coal | As prod. | Be coal | Be prod. | Co coal | Co prod. | Cr coal | Cr prod. | Mn coal | Mn prod. | Ni coal | Ni prod. | P coal | P prod. | Pb coal | Pb prod. | Sb coal | Sb prod. | Se coal | Se prod. | Th coal | Th prod. | U coal | U prod. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C32773 | 1 | -100 | 8.72 | 5.01 | 1.3 | 0.5 | 1 | 1.0 | 2.3 | 2.0 | 12 | 11 | 39 | 13 | 11 | 10 | 44 | 22 | <6 | <5 | 0.2 | 0.2 | 1.9 | 1.2 | 1.2 | 1.0 | 1.7 | <1 |
| C32774 | 1 | -100 | 7.07 | 2.77 | 20 | 9.1 | 4 | 11.0 | 3.1 | 0.9 | 5.8 | 4.4 | 18 | 5.0 | 15 | 4 | 87 | 52 | 36 | 22 | 1.2 | 0.8 | 1.2 | 0.9 | 0.8 | 0.6 | <0.8 | <1 |
| C32777 | 1 | -100 | 14.52 | 7.87 | 5.1 | 1.2 |  | 2.2 | 1.5 | 1.6 | 11 | 10 | 205 | 35 | 7 | 6 | 44 | 17 | 14 | 9 | 1.1 | 0.8 | 1.6 | 1.0 | 1.5 | 0.9 | 1.1 | 0.7 |
| C32778 | 1 | -100 | 9.8 | 4.79 | 10 | 2.9 | 1.2 | 4.8 | 4.6 | 3.8 | 12 | 9.4 | 38 | 12 | 31 | 25 | 87 | 39 | <6 | <5 | 2.2 | 2.2 | 1.9 | 1.0 | 1.1 | 1.2 | 0.9 | 1.3 |
| C32782 | 1 | -100 | 11.62 | 5.89 | 2.4 | 0.9 | 2.2 | 2.2 | 1.6 | 1.2 | 17 | 9.7 | 55 | 15 | 7 | 7 | 87 | 26 |  |  | 0.5 | 0.4 | 1.9 | 1.9 | 1.1 | 0.9 | 1.3 | 1.4 |
| C32785 | 1 | -100 | 9.75 | 4.38 | 2.3 | 0.7 | <1.0 |  | 0.3 | 1.8 | 17 | 12 | 39 | 12 | 18 | 11 | 131 | 31 |  |  | 0.4 | 0.2 | 3.9 | 1.0 | 1.3 | 1.0 | 1.8 | 1.4 |
| C32797 | 1 | -100 | 10.29 | 5.59 | 4 | 1.1 |  | 3.1 | 2.6 | 2.3 | 12 | 11 | 32 | 12 | 16 | 14 | 87 | 31 |  |  | 0.6 | 0.6 | 1.4 | 1.1 | 1.5 | 1.1 | 1.9 | 1.8 |
| C32814 | 1 | -100 | 6 | 3.36 | 6.4 | 2.6 | 2 | 2.3 |  | 1.5 | 5.7 | 6.2 | 30 | 7.0 | 11 | 10 | 30 | 17 | 23 | 14 | 1.9 | 1.5 | 1.3 | 1.0 | 0.6 | 0.6 | 8.0 | 6.8 |
| C32779 | 2 | -100 | 9.63 | 3.86 | 1.7 | 0.8 | <1.0 | 2.3 | 2.5 | 2.1 | 17 | 13 | 29 | 9.0 | 14 | 6 | 44 | 17 | 7 | 6 | 0.4 | 0.3 | 2.3 | 1.2 | 1.4 | 0.9 | 3.1 | 3.1 |
| C32794 | 2 | -100 | 10.52 | 4.32 | 2.3 | 0.8 | 1.1 | 1.1 | 2.2 | 1.9 | 17 | 12 | 11 | 11 | 11 | 8 | 87 | 35 | 15 | 7 | 0.3 | 0.2 | 1.9 | 1.1 | 1.7 | 1.1 | 2.0 | 1.8 |
| C32798 | 2 | -100 | 13.16 | 6.1 | 2.2 | 1.0 | <1.0 |  | 2.8 | 2.1 | 23 | 12 | 54 | 16 | 18 | 17 | 305 | 35 | 12 | <5 | 0.3 | 0.3 | 3.2 | 1.3 | 1.6 | 1.2 | 2.7 | 2.6 |
| C32800 | 2 | -100 | 11.39 | 7.23 | 2 | 1.0 |  | 1.4 | 3.3 | 2.1 | 23 | 14 | 30 | 16 | 16 | 9 | 305 | 109 |  |  | 0.4 | 0.4 | 1.5 | 1.5 | 1.2 | 1.2 | 2.9 | 2.3 |
| C32813 | 2 | -100 | 14.7 | 7.88 | 2.4 | 0.9 | 1.4 | 2.1 | 2.8 | 2.7 | 47 | 17 | 40 | 16 | 24 | 6 | 305 | 13 | 13 |  | 0.7 | 0.5 | 5.4 | 2.9 | 2.1 | 1.5 | 3.7 | 2.8 |
| C32815 | 2 | -100 | 12.03 | 5.01 | 3 | 0.9 | 1.8 | 3.5 | 3.5 | 2.5 | 11 | 11 | 61 | 18 | 10 | 9 | 44 | 13 | 12 | <5 | 0.6 | 0.4 | 2.1 | 1.0 | 1.7 | 1.2 | 1.0 | 1.9 |
| C32784 | 3 | -100 | 8.13 | 3.32 | 18 | 9.3 | 1 | 1.0 | 2.7 | 4.0 | 14 | 8.9 | 17 | 6.5 | 15 | 9 | 44 | 31 | 16 | 10 | 1.1 | 1.0 | 1.4 | 1.1 | 1.4 | 0.9 | 1.0 | <1 |
| C32795 | 3 | -100 | 5.76 | 2.79 | 3.6 | 2.2 |  |  | 4.2 | 4.0 | 8.6 | 7.0 | 11 | 4.0 | 18 | 14 | 44 | 31 |  |  | 1.1 | 1.1 | 1.1 | 0.8 | 1.2 | 0.8 | 0.6 | <.5 |
| C32799 | 3 | -100 | 11.42 | 3.48 | 17 | 1.6 |  |  | 4.8 | 3.0 | 12 | 8.6 | 64 | 5.0 | 15 | 13 | 436 | 275 | 16 |  | 3.6 | 3.0 | 1.3 | 0.9 | 1.6 | 0.9 | 0.7 | 0.7 |
| C32801 | 3 | -100 | 8.36 | 4.71 | 10 | 4.6 |  | 2.5 | 4.4 | 2.1 | 12 | 9.9 | 21 | 9.0 | 14 | 7 | 44 | 21 |  |  | 0.6 | 0.6 | 2.5 | 2.1 | 1.5 | 1.1 | 1.0 | 1.0 |
| C32803 | 3 | -100 | 9.19 | 5.25 | 4.1 | 1.8 | 1.6 | 1.0 | 2.7 | 2.1 | 12 | 11 | 28 | 10 | 13 | 7 | 44 | 17 |  |  | 0.4 | 0.5 | 1.3 | 0.9 | 1.6 | 1.3 | 1.1 | 1.3 |
| C32661 | 4H | -100 | 8.17 | 4.01 | 3.4 | 1.5 | 1.2 | 1.6 | 3.9 | 2.3 | 16 | 13 | 20 | 7.0 | 14 | 5 | 44 | 17 | 19 | 12 | 0.5 | 0.3 | 2 | 1.0 | 1.5 | 1.1 | 7.5 | 6.3 |
| C32665 | 4H | -100 | 9.39 | 3.8 | 4.4 | 1.3 | 1.1 | 1.4 | 3.6 | 2.8 | 13 | 12 | 25 | 6.0 | 11 | 9 | 44 | 13 | 19 | 6 | 0.4 | 0.3 | 1.7 | 0.9 | 1.6 | 1.1 | 5.7 | 5.6 |
| C32771 | 4H | -100 | 12.57 | 4.29 | 3.7 | 1.3 | 1.5 | 2.7 | 4.1 | 2.3 | 14 | 12 | 36 | 8.0 | 10 | 5 | 44 | 17 | 22 | 8 | 0.3 | 0.2 | 1.8 | 0.8 | 1.8 | 1.1 | 2.2 | 2.1 |
| C32776 | 4H | -100 | 9.27 | 4.16 | 2.7 | 1.1 | 1.4 | 1.0 | 3.6 | 3.9 | 15 | 13 | 38 | 10 | 12 | 9 | 44 | 17 | 10 | 11 | 0.6 | 0.5 | 1.7 | 1.2 | 1.4 | 0.9 | 1.8 | 1.9 |
| C32662 | 45 | -100 | 7 | 3.67 | 14 | 5.2 |  | 1.1 | 4.4 | 2.7 | 10 | 7.8 | 15 | 6.0 | 17 | 12 | 175 | 74 | 23 | 13 | 1.0 | 0.8 | 2.3 | 0.9 | 1.9 | 1.1 | 1.9 | 1.6 |
| C32772 | 45 | -100 | 9.33 | 4.34 | 8 | 2.6 | <1.0 | 1.1 | 3.9 | 3.7 | 9.2 | 8.2 | 39 | 8.0 | 13 | 9 | 87 | 44 | 27 | 23 | 0.7 | 0.7 | 1.3 | 1.0 | 1.3 | 1.0 | <1.0 | <1 |
| C32781 | 45 | -100 | 9.71 | 5.19 | 4.3 | 1.4 | 1.2 | 2.0 | 2.7 |  | 13 | 9.9 | 37 | 10 | 11 | 9 | 44 | 13 | 46 | 23 | 1.4 | 1.0 | 2.5 | 1.3 | 1.2 | 1.0 | 2.0 | 1.5 |
| C32793 | 45 | -100 | 14.14 | 3.59 | 33 | 8.4 |  |  | 5.5 |  | 13 | 7.0 | 39 | 8.0 | 22 | 15 | 175 | 57 | 36 | 11 | 1.2 | 1.1 | 1.1 | 0.9 | 1.8 | 0.8 | 0.8 | 0.6 |
| mean | all |  | 10.06 | 4.69 | 7.1 | 2.4 | 1.3 | 2.4 | 3.4 | 3.4 | 14 | 11 | 41 | 11 | 15 | 10 | 92 | 41 | 19 | 11 | 0.9 | 0.7 | 1.9 | 1.1 | 1.4 | 1.0 | 2.2 | 2.0 |
| stdev | all |  | 2.37 | 1.35 | 7.3 | 2.5 | 0.8 | 2.1 | 1.0 | 1.0 | 6.7 | 3.4 | 35 | 6 | 5 | 5 | 89 | 51 | 11 | 8 | 0.7 | 0.6 | 1.9 | 0.4 | 0.3 | 0.2 | 1.9 | 1.7 |
| C32773 | 1 | -200 | 8.72 | 4.87 | 1.3 | 0.6 | 1 | 1.6 | 2.3 | 1.8 | 12 | 10 | 39 | 24 | 11 | 8 | 44 | 26 | <6 | <5 | 0.2 | 0.1 | 1.9 | 0.9 | 1.2 | 0.9 | 1.7 | <1 |
| C32774 | 1 | -200 | 7.07 | 2.65 | 20 | 7.4 | 4 | 9.0 | 3.1 | 1.4 | 5.8 | 6.5 | 18 | 5.0 | 15 | 6 | 87 | 52 | 15 | 5 | 1.2 | 0.9 | 1.2 | 0.5 | 0.8 | 0.6 | <0.8 | <1 |
| C32794 | 2 | -200 | 10.52 | 5.69 | 2.3 | 1.0 | 1.1 | 2.1 | 2.8 | 1.8 | 12 | 7.9 | 40 | 19 | 14 | 6 | 44 | 26 | 13 | 5 | 0.3 | 0.2 | 1.6 | 0.9 | 1.4 | 0.9 | 2 | 1.6 |
| C32813 | 2 | -200 | 14.7 | 5.67 | 2.4 | 0.8 | 1.4 | 2.7 | 3.5 | 2.3 | 42 | 21 | 40 | 17 | 24 | 12 | 305 | 96 | 40 | 32 | 0.7 | 0.6 | 5.4 | 1.6 | 2.1 | 1.2 | 3.7 | 3.2 |
| C32784 | 3 | -200 | 8.13 | 3.21 | 18 | 6.0 | 1.8 | 2.4 | 4.2 | 2.8 | 11 | 9.0 | 11 | 9.0 | 15 | 9 | 44 | 35 | 19 | 6 | 1.1 | 0.9 | 1.4 | 0.8 | 1.4 | 0.8 | 2 | 1.0 |
| C32665 | 4H | -200 | 9.39 | 3.47 | 4.4 | 0.9 | 1.2 | 1.9 | 3.6 | 2.8 | 13 | 12 | 17 | 11 | 11 | 9 | 44 | 17 | 6 | 7 | 0.4 | 0.2 | 1.6 | 0.8 | 1.6 | 1.0 | 5.7 | 5.3 |
| C32771 | 4H | -200 | 12.57 | 5.17 | 3.7 | 1.0 | 1.1 | 1.8 | 4.1 | 2.8 | 14 | 14 | 36 | 20 | 10 | 9 | 44 | 22 | 22 | 7 | 0.3 | 0.2 | 1.4 | 0.7 | 1.8 | 1.2 | 2.2 | 2.1 |
| C32772 | 45 | -200 | 9.33 | 3.62 | 8 | 1.7 | 1.1 | 1.4 | 3.4 | 2.3 | 9.2 | 9.1 | 39 | 15 | 13 | 9 | 87 | 39 | 27 | 11 | 0.7 | 0.6 | 1.7 | 0.7 | 1.3 | 0.9 | <1 | <1 |
| mean | all |  | 10.05 | 4.29 | 7.5 | 2.4 | 1.6 | 2.9 | 3.4 | 2.3 | 15 | 11 | 32 | 15 | 14 | 9 | 87 | 39 | 32 | 37 | 0.6 | 0.5 | 2.0 | 0.9 | 1.5 | 0.9 | 2.6 | 2.3 |
| stdev | all |  | 2.33 | 1.12 | 6.9 | 2.5 | 0.9 | 2.4 | 0.6 | 0.5 | 10.5 | 4.3 | 9 | 6 | 4 | 2 | 84 | 24 | 71 | 71 | 0.4 | 0.3 | 1.3 | 0.3 | 0.4 | 0.2 | 2.2 | 1.9 |

* blank spaces indicate that no data were available at the time of this writing

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**Table 3.** Percent changes in ash and HAPs contents as a result of F-S separation of 27 samples of marketed Illinois coals ground to -100 mesh. Each clean F-S product contained 80% of the combustible materials of its parent sample. Negative values indicate decreases and positive values enrichments. In the statistical computations, one-half the detection limit was used for all values below the detection limit.*

| FEED COAL NO. | REGION | Ash | As | Be | Co | Cr | Mn | Ni | P | Pb | Sb | Se | Th | U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C32773 | 1 | -43 | -62 | 0 | -13 | -8 | -67 | -9 | -5D | -17 | 0 | -37 | -17 | -71 |
| C32774 | 1 | -61 | -55 | 175 | -71 | -24 | -72 | -73 | -40 | | -33 | -25 | -25 | 25 |
| C32777 | 1 | -46 | -76 | -83 | 7 | -9 | -83 | -14 | -61 | -39 | -27 | -31 | -18 | -36 |
| C32778 | 1 | -51 | -71 | 118 | -17 | -22 | -68 | -19 | -55 | -36 | 0 | -33 | -20 | 44 |
| C32782 | 1 | -49 | -63 | 340 | -25 | -31 | -73 | 0 | -70 | -17 | -20 | -47 | -18 | 8 |
| C32785 | 1 | -55 | -70 | | -31 | -29 | -69 | -39 | -76 | | -50 | -51 | -23 | -22 |
| C32797 | 1 | -46 | -73 | | -23 | -15 | -63 | -13 | -64 | | 0 | -29 | -27 | -5 |
| C32814 | 1 | -44 | -59 | 55 | -40 | 9 | -77 | -17 | -57 | -39 | -21 | -15 | 0 | -15 |
| C32779 | 2 | -60 | -53 | 360 | -35 | -24 | -69 | -45 | -61 | -14 | -25 | -48 | -31 | 0 |
| C32794 | 2 | -59 | -65 | 109 | -25 | 0 | -73 | -43 | -61 | -33 | -33 | -42 | -21 | -10 |
| C32798 | 2 | -54 | -64 | 120 | -42 | -39 | -70 | -6 | -60 | -79 | 0 | -59 | -24 | -4 |
| C32800 | 2 | -37 | -50 | | -18 | -26 | -53 | -44 | -60 | | 0 | -46 | -25 | -21 |
| C32813 | 2 | -46 | -58 | 0 | -40 | -48 | -60 | -38 | -64 | -46 | -29 | -46 | -29 | -24 |
| C32815 | 2 | -58 | -70 | 320 | -37 | -21 | -70 | -40 | -70 | -79 | -33 | -52 | -29 | 0 |
| C32784 | 3 | -59 | -48 | 94 | -40 | -19 | -62 | -40 | -30 | | -9 | -21 | -36 | -50 |
| C32795 | 3 | -52 | -39 | 0 | -4 | -19 | -64 | -22 | -30 | -38 | 0 | -27 | -33 | -58 |
| C32799 | 3 | -70 | -91 | | -9 | -28 | -92 | -13 | -37 | | -17 | -31 | -44 | 0 |
| C32801 | 3 | -44 | -54 | | -32 | -17 | -57 | -50 | -30 | | 0 | -27 | -27 | 0 |
| C32803 | 3 | -43 | -56 | | -22 | -8 | -64 | -46 | -61 | | -25 | -40 | -19 | 18 |
| C32661 | 4H | -51 | -56 | 56 | -54 | -19 | -65 | -64 | -61 | -37 | -40 | -50 | -33 | -16 |
| C32665 | 4H | -60 | -70 | -17 | -42 | -8 | -76 | -55 | -70 | -68 | -25 | -47 | -31 | -2 |
| C32771 | 4H | -66 | -76 | 45 | -54 | -14 | -78 | -10 | -61 | -41 | -33 | -43 | -39 | -5 |
| C32776 | 4H | -55 | -63 | -7 | -36 | -13 | -74 | -42 | -61 | 30 | -14 | -29 | -36 | 6 |
| C32662 | 4S | -48 | -63 | 93 | -36 | -22 | -60 | -29 | -58 | -52 | -20 | -31 | -37 | -16 |
| C32772 | 4S | -53 | -68 | 0 | -41 | -11 | -79 | -31 | -49 | -15 | -14 | -23 | -23 | 0 |
| C32781 | 4S | -47 | -67 | 120 | -37 | -17 | -73 | -18 | -70 | -30 | -29 | -48 | -25 | -25 |
| C32793 | 4S | -75 | -75 | 67 | -33 | -46 | -79 | -32 | -67 | -69 | -8 | -18 | -56 | -25 |
| mean all | | -53 | -64 | 94 | -31 | -20 | -70 | -32 | -57 | -38 | -19 | -37 | -28 | -11 |
| stdev all | | 9 | 10 | 117 | 16 | 12 | 8 | 18 | 13 | 25 | 14 | 12 | 10 | 24 |

* blank spaces indicate that no data were available at the time of this writing.

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**Table 4.** Percent changes in ash and HAPs contents as a result of F-S separation of 8 samples of marketed Illinois coals ground to -100 and -200 mesh. Each clean F-S product contained 80% of the combustible materials of its parent sample. Negative values indicate decreases and positive values enrichments. In the statistical computations, one-half the detection limit was used for all values less than the detection limit.*

| FEED COAL NO. | REGION | MESH SIZE | Ash | As | Be | Co | Cr | Mn | Ni | P | Pb | Sb | Se | Th | U |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C32773 | 1 | -100 | -43 | -62 | 0 | -13 | -8 | -67 | -9 | -50 | -17 | 0 | -37 | -17 | -71 |
| C32774 | 1 | -100 | -61 | -55 | 175 | -71 | -24 | -72 | -73 | -40 | | -33 | -25 | -25 | 25 |
| C32794 | 2 | -100 | -59 | -65 | 109 | -25 | 0 | -73 | -43 | -61 | -33 | -33 | -42 | -21 | -10 |
| C32813 | 2 | -100 | -46 | -58 | 0 | -40 | -48 | -60 | -38 | -64 | -46 | -29 | -46 | -29 | -24 |
| C32784 | 3 | -100 | -59 | -48 | 94 | -40 | -19 | -62 | -40 | -30 | | -9 | -21 | -36 | -50 |
| C32665 | 4H | -100 | -60 | -70 | -17 | -42 | -8 | -76 | -55 | -70 | -68 | -25 | -47 | -31 | -2 |
| C32771 | 4H | -100 | -66 | -76 | 45 | -54 | -14 | -78 | -10 | -61 | -41 | -33 | -43 | -39 | -5 |
| C32772 | 4S | -100 | -53 | -68 | 0 | -41 | -11 | -79 | -31 | -49 | -15 | -14 | -23 | -23 | 0 |
| mean | all | | -56 | -63 | 51 | -41 | -17 | -71 | -37 | -53 | -37 | -22 | -36 | -28 | -17 |
| stdev | all | | 7 | 8 | 64 | 16 | 14 | 7 | 20 | 13 | 18 | 12 | 10 | 7 | 29 |
| C32773 | 1 | -200 | -44 | -54 | 60 | -22 | -17 | -38 | -27 | -41 | -17 | -50 | -53 | -25 | -71 |
| C32774 | 1 | -200 | -63 | -63 | 125 | -55 | 12 | -72 | -60 | -40 | | -25 | -58 | -25 | 25 |
| C32794 | 2 | -200 | -46 | -57 | 91 | -36 | -34 | -53 | -57 | -41 | 83 | -33 | -53 | -36 | -20 |
| C32813 | 2 | -200 | -61 | -67 | 93 | -34 | -50 | -58 | -50 | -69 | -81 | -14 | -70 | -43 | -14 |
| C32784 | 3 | -200 | -61 | -67 | 33 | -33 | -18 | -47 | -40 | -20 | -20 | -18 | -43 | -43 | 0 |
| C32665 | 4H | -200 | -63 | -80 | 58 | -36 | -8 | -56 | -18 | -61 | -68 | -50 | -53 | -38 | -7 |
| C32771 | 4H | -200 | -59 | -73 | 64 | -32 | 0 | -44 | 10 | -50 | -68 | -33 | -50 | -33 | -5 |
| C32772 | 4S | -200 | -61 | -79 | 40 | -28 | -1 | -62 | -31 | -55 | -59 | -14 | -46 | -31 | 0 |
| mean | all | | -57 | -68 | 71 | -35 | -15 | -54 | -34 | -47 | -33 | -30 | -53 | -34 | -12 |
| stdev | all | | 7 | 9 | 29 | 9 | 19 | 10 | 22 | 14 | 53 | 14 | 8 | 7 | 26 |

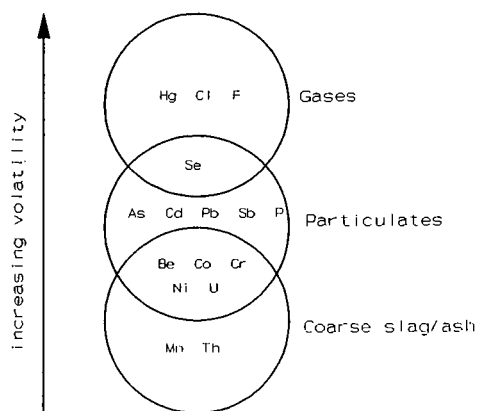* blank spaces indicate that no data were available at the time of this writing.

**Figure 1.** Enrichment of HAPs in different coal combustion and gasification products (after Clarke and Sloss, 1992).
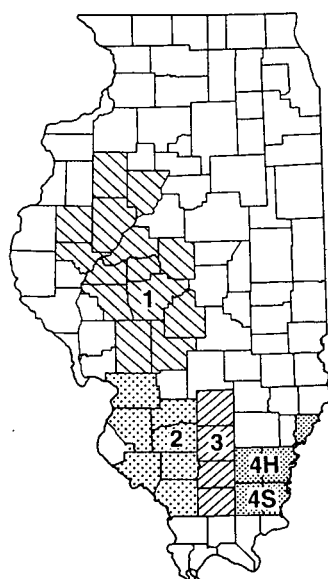


**Figure 2.** Sample regions of Illinois coal field. Region 4 was subdivided by seam into Herrin (H) and Springfield (S) coals.
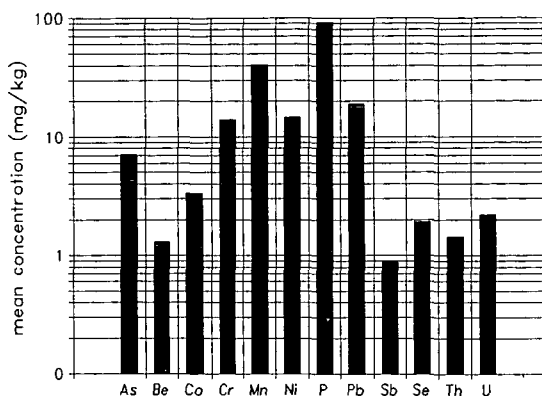
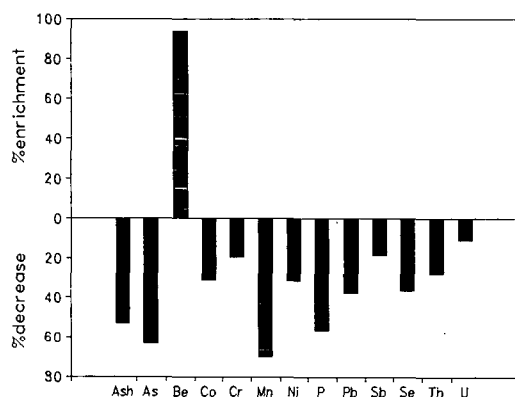**Figure 3.** Mean concentrations of 12 HAPs in 27 samples of marketed Illinois coals.



**Figure 4.** Average estimated changes in concentrations of 12 HAPs in 27 samples of marketed Illinois coals ground to -100 mesh if an advanced gravity separation process were applied and 80% of the combustible materials recovered from the process.
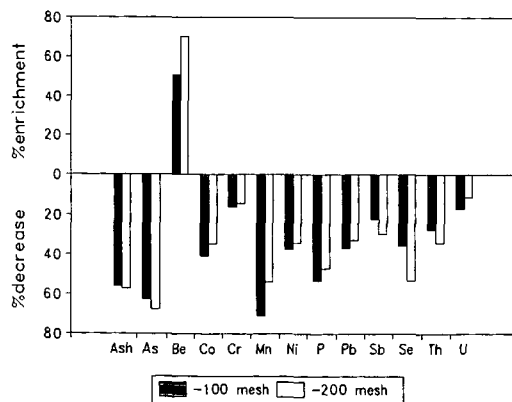


**Figure 5.** Average estimated changes in concentrations of 12 HAPs in 8 samples of marketed Illinois coals ground to -100 and -200 mesh if an advanced gravity separation process were applied and 80% of the combustible materials recovered from the process.